

MULTIJUNCTION SOLAR CELL ISO-JUNCTION DARK CURRENT STUDY

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ABSTRACT

Single-crystal multijunction solar cells show great promise for achieving 30-40% conversion efficiency under air mass zero (AM0) conditions, and have been identified as an enabling technology for next-generation government and commercial satellites. In this note we report on an approach to better understand the dark current-voltage (I-V) behavior in multijunction solar cells and its effect on conversion efficiency. This technique is based on determining the impact of dark-current behavior within individual p-n junctions on monolithic triple-junction GaInP₃/GaAs/Ge solar cell performance. The GaInP₃/GaAs/Ge tandem solar cells used in this study were developed, in part, under the US Air Force's Manufacturing Technology (ManTech) Program and exhibited measured efficiencies of 24-25% (AM0).

Introduction

Today's spacecraft have greater power requirements than ever before. More electrical energy is needed to run increasingly complicated and diversified payloads that are assigned longer and more complex missions. To support these missions, the US Air Force Research Laboratory (AFRL) has been involved in the research and development of high-efficiency III-V semiconductor-based multijunction solar cells since 1990, including programs to develop the first large-area 2-junction GaInP₃/GaAs, 3-junction GaInP₃/GaAs/Ge, and most recently, novel 4-junction solar cell designs.

Solar cell dark I-V behavior is known to play an important role in limiting single junction solar cell open-circuit voltage (V_{oc}), fill factor (FF), and conversion efficiency (η). This can be seen from Equation 1,

$$P_m = I_m V_m = (I_{sc} - I_{dmax}) \left(\frac{AkT}{q} \right) \ln \left(\frac{I_{dmax}}{I_0} \right) \quad (1)$$

where P_m , I_m and V_m are the maximum power, current, and voltage, respectively, at the cell's

maximum power point (MPP), I_{sc} is the short circuit current, I_{dmax} is the magnitude of dark current at MPP, and I_0 and A are the values of reverse saturation current and ideality factor, respectively, associated with I_{dmax} . Clearly the magnitude of both I_{dmax} and I_0 will critically affect P_m and overall efficiency. Consequently, a large volume of work [1-4] has been devoted to the identification and source reduction of dark current in solar cells, notably in single junction Si and GaAs solar cells.

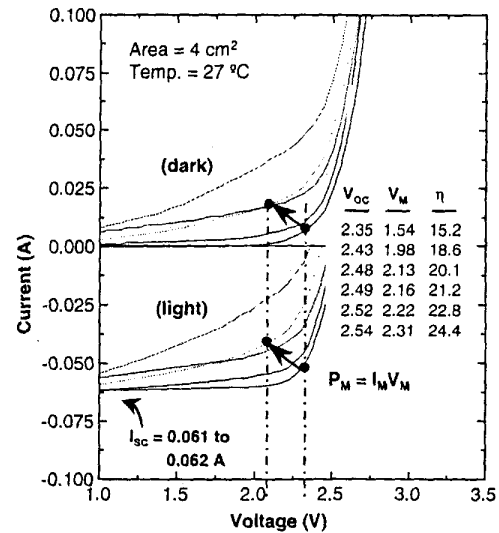


Fig. 1. Linear plot of dark and light I-V characteristics of a GaInP₃/GaAs/Ge solar cell. A direct correlation is shown between decreasing efficiency with increasing dark current.

While detailed studies of dark I-V behavior for GaInP₃ p-n diodes and solar cells have been reported [5], detailed analysis of dark I-V behavior of multijunction solar cells, and in particular, monolithic GaInP₃/GaAs/Ge solar cells, has not been addressed in detail. In this study we investigated the impact of individual (iso-) junction dark current behavior on 3-junction solar cell performance.

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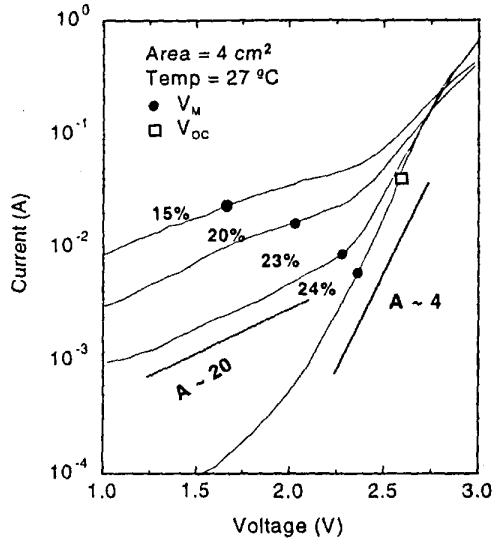


Fig. 2. Dark I-V characteristics of a GaInP₂/GaAs/Ge (3-junction) solar cell correlated with voltage at the maximum power point, V_M, and efficiency.

Experimental

As shown in Figures 1 and 2, a direct correlation is evident between high dark current values and reduced MPP. In all cells measured (~30), I_{sc} was nearly constant as shown in Figure 1, and significant variations in performance resulted from large “leaky” dark currents. Figure 3 shows the basic equivalent circuit diagram for a single junction p-n solar cell. The dark current mechanisms shown by the diode symbols represent current due to diffusion, recombination and tunneling. These dark currents directly subtract from the light-generation short-circuit current (I_{sc}) according to

$$I = I_{sc} - I_{diff} e^{\left(\frac{qV}{A_{diff}k_B T}\right)} - I_{rec} e^{\left(\frac{qV}{A_{rec}k_B T}\right)} \quad (2)$$

where the contribution due to tunneling can be neglected near the MPP for high quality devices. I_{diff} and I_{rec} are the reverse saturation currents due to carrier diffusion and recombination, respectively, V is the voltage across the diode junction, and A_{diff} and A_{rec} are the diode ideality factors. Values for A_{diff} ~ 1.0 and A_{rec} ~ 2 are predicted according to the classic Shockley and Sah-Noyce-Shockley diodes models, respectively. It is noted that premature dark current mechanism

“turn-on” therefore critically limits photo-voltage at MPP and overall efficiency.

Values for I_{diff}, I_{rec}, A_{diff} and A_{rec} are generally easily obtained for single junction solar cells using the simplified diode equation

$$I = I_t \left(\frac{qV}{A k_B T} \right) \quad V_i \gg k_B T \quad (3)$$

where the dark current-voltage curve is generally dominated by the A~2 current mechanism at lower voltages than the A~1 dark currents [5].

Of special interest was the use of Equation 3 to determine values of A for the 3-junction solar cells in Figure 1. Typical observed values for A near the MPP for well-behaved cells (24-25% efficient) were A~4 - 5. For single junction solar cells a value of A > 2 would normally indicate dominance of tunneling dark current. However, multijunction solar cells have multiple dark current mechanisms acting simultaneously in multiple junctions which complicates the interpretation of A values.

To understand the high observed values of A in the 3-junction GaInP₂/GaAs/Ge solar cells, we

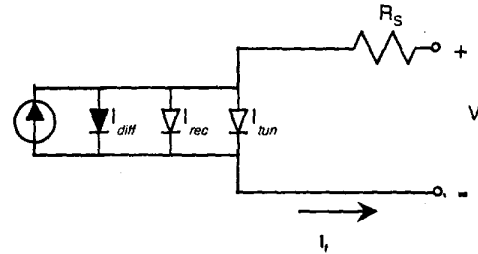


Fig. 3. Equivalent electrical circuit depicting dark current mechanisms for a multijunction device.

analyzed the equivalent electrical circuit model shown in Figure 4. We assumed that either a single dark current mechanism dominates each junction at MPP or a combination of diffusion and recombination dark current was present resulting in values of A between 1 and 2. Using Kirchhoff's voltage law, the sum of the voltage drops around the GaInP₂/GaAs/Ge triple-junction circuit shown in Figure 4 may be expressed as

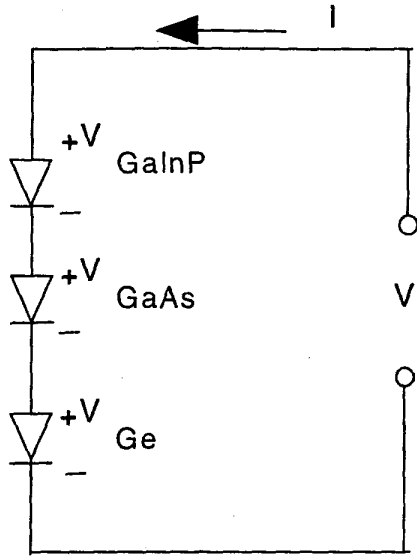


Fig. 4. Equivalent electrical circuit model assuming single dominant dark current mechanism per junction.

$$V - V_{\text{GaInP}_2} - V_{\text{GaAs}} - V_{\text{Ge}} = 0 \quad (4)$$

where V is the total voltage across the triple junction device, and V_{GaInP_2} , V_{GaAs} , and V_{Ge} are the voltage drops across their respective individual junctions. Substituting Equation 4 into Equation 3 for the GaInP_2 junction yields

$$I = I_{\text{GaInP}_2} e^{\left(\frac{q(V - V_{\text{GaAs}} - V_{\text{Ge}})}{A_{\text{GaInP}_2} k_B T} \right)} \quad (5)$$

where I_{GaInP_2} , V_{GaInP_2} , and A_{GaInP_2} are the saturation current, voltage, and ideality factor for the GaInP_2 junction. Then, from Equation 3

$$V_{\text{GaAs}} = \frac{A_{\text{GaAs}} k_B T}{q} \ln \left(\frac{I}{I_{\text{GaAs}}} \right) \quad (6)$$

with similar results for V_{Ge} . Substituting these expressions for V_{GaAs} and V_{Ge} into Equation 5 yields

$$I = I_{\text{GaInP}_2} e^{\left(\frac{qV}{A_{\text{GaInP}_2} k_B T} - \frac{A_{\text{GaAs}}}{A_{\text{GaInP}_2}} \ln \left(\frac{I}{I_{\text{GaAs}}} \right) - \frac{A_{\text{Ge}}}{A_{\text{GaInP}_2}} \ln \left(\frac{I}{I_{\text{Ge}}} \right) \right)} \quad (7)$$

which may be re-written as

$$I = I_{\text{GaInP}_2}^{\left(\frac{A_{\text{GaInP}_2}}{A_{\text{total}}} \right)} I_{\text{GaAs}}^{\left(\frac{A_{\text{GaAs}}}{A_{\text{total}}} \right)} I_{\text{Ge}}^{\left(\frac{A_{\text{Ge}}}{A_{\text{total}}} \right)} e^{\left(\frac{qV}{A_{\text{total}} k_B T} \right)} \quad (8)$$

where

$$A_{\text{total}} = A_{\text{GaInP}_2} + A_{\text{GaAs}} + A_{\text{Ge}} \quad (9)$$

Equation 9 explains the high observed values of $A \sim 4 - 5$ for the 3-junction solar cells, where typical measured values of A for dark current at MPP for individual junctions (discussed in next section) were $\sim 1.5 - 2$. We also see from Equation 8 the important role the values of reverse saturation current, I_{GaInP_2} , I_{GaAs} , I_{Ge} for individual junctions play. It is noted that in good cells the values for reverse saturation currents are determined by the dominant mechanism, diffusion or recombination, where I_{diff} is generally many orders of magnitude lower than I_{rec} [5]. The relative affect of reverse saturation current on total dark is shown in Figure 5, where each value of I_{GaInP_2} , I_{GaAs} , and I_{Ge} is varied over 3 orders of magnitude, while the other two values of reverse saturation current remain constant.

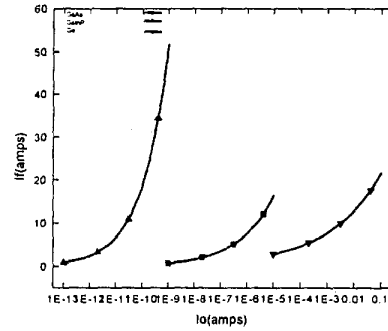


Fig. 5. Results of sensitivity analysis showing variation of forward current with three decades of change in the reverse saturation current.

Iso-Junction Measurements

To better understand the observed values for A and the role that individual dark current mechanisms play in each junction, we developed an "iso-junction" test structure shown in Figure 6, to allow us to physically probe individual junctions and measure individual ideality factors and reverse saturation currents for the 3-junction $\text{GaInP}_2/\text{GaAs}/\text{Ge}$ solar cell. Dark current measurements were taken using standard equipment from 0.0 V to a voltage corresponding to a current limit of 0.1 A. In all cases, this range included the knee of the diode I-V curve. Currents were normalized to device area to produce current density

